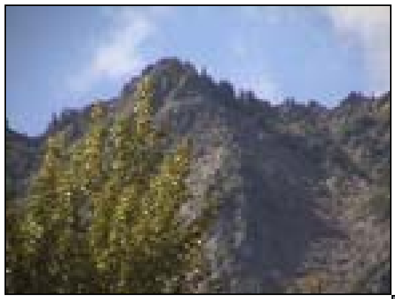
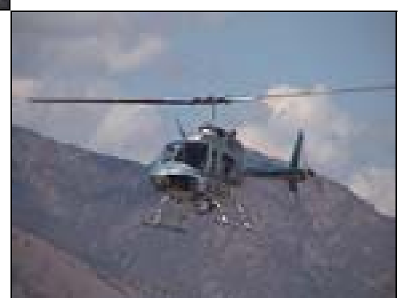
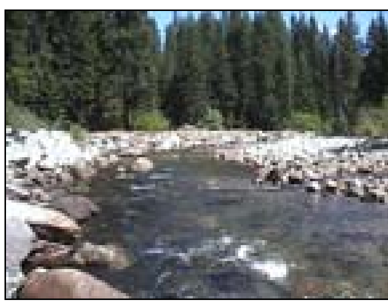
Aerial Surveys in the Wenatchee River Sub-Basin, WA
Thermal Infrared and Color Videography

December 4, 2003







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Preliminary Report

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Introduction

Watershed Sciences, LLC (WS, LLC) conducted airborne thermal infrared (TIR) remote sensing surveys on selected streams in the Wenatchee River Sub-Basin, WA. The objective of the project was to collect TIR and color video imagery in order to characterize the thermal regime of the river and support ongoing Total Maximum Daily Load (TMDL) analysis.

Water temperatures vary naturally along the stream gradient due to topography, channel morphology, substrate composition, riparian vegetation, ground water exchanges, and tributary influences. Stream temperatures are also affected by human activities within the watershed. TIR images provide information about spatial stream temperature variability and can illustrate changes in the interacting processes that determine stream temperature. In most cases, these processes are extremely difficult to detect and quantify using traditional ground-based monitoring techniques.

It is the aim of this report to: 1) document methods used to collect and process the TIR images, 2) present spatial temperature patterns, and 3) highlight interesting features observed during image analysis. Thermal infrared and associated true color video images are included in the report in order to illustrate significant thermal features. An associated ArcView 3.2 GIS[1] database includes all of the images collected during the survey and is structured to allow analysis at finer scales.

Methods

Data Collection

Images were collected with TIR (8-12μ) and visible-band cameras attached to a gyro-stabilized mount on the underside of a helicopter. The two sensors were aligned to present the same ground area, and the helicopter was flown longitudinally along the stream channel with the sensor looking straight down. Thermal infrared images were recorded directly from the sensor to an on-board computer in a format in which each pixel contained a measured radiance value. The recorded images maintained the full 12-bit dynamic range of the sensor. The individual images were referenced with time and position data provided by a global positioning system (GPS).

A consistent altitude above ground level was maintained in order to preserve the scale of the imagery throughout the survey. The ground width and spatial resolution presented by the TIR image vary based on the flight altitudes. The flight altitude is selected prior to the flight based on average channel width and morphology. During the flight, images were collected sequentially with approximately 40% vertical overlap. The flight was conducted in the mid-afternoon in order to capture heat of the day conditions.

[1] Geographic Information System

The airborne surveys in the Wenatchee River Sub-Basin were conducted during the mid-afternoons of August 11-12, 2003 (Figure 1). Each stream was flown upstream from the mouth. Table 1 summarizes the time, extent, and image size/resolution for each surveyed stream.

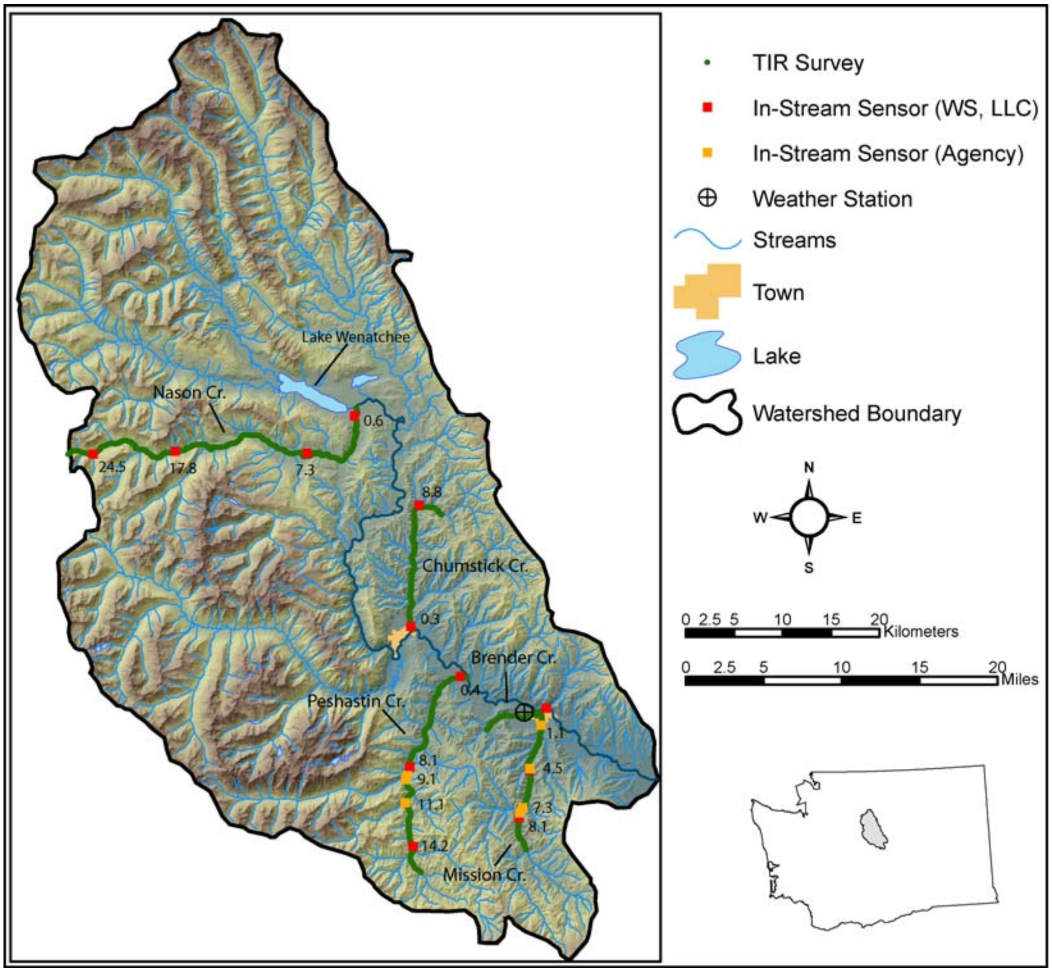

Figure 1 – Map showing the extent of the airborne TIR flights in the Wenatchee River Sub-Basin. The plot shows the location of the portable weather station and the location of in-stream sensors used to ground truth radiant temperatures derived from TIR images labeled by river mile (rm). Agency sensors indicate data received from WA DOE.

Stream	Survey Date	Survey Time	Survey Extent	River Miles	Image Width Meter (ft)	TIR Image Pixel Size Meter (ft)
Mission Cr.	11-Aug	13:28-13:49	Mouth to East Fork	11.4	118 (388)	0.37 (1.21)
Brender Cr.	11-Aug	13:57-14:06	Mouth to Brisky Canyon	4.2	107 (353)	0.34 (1.10)
Peshastin Cr.	11-Aug	14:14-14:42	Mouth to Scotty Cr.	16.3	150 (494)	0.48 (1.54)
Chumstick Cr.	11-Aug	14:56-15:25	Mouth upstream past Second Cr.	10.5	118 (388)	0.37 (1.21)
Nason Cr.	12-Aug	13:53-14:44	Mouth to headwaters	25.6	150 (494)	0.48 (1.54)

Table 1 – Flight date, time, and extent for each stream surveyed with airborne TIR remote sensing in the Wenatchee River Sub-Basin.

Prior to the flight, WS, LLC deployed in-stream data loggers in order verify the accuracy of the TIR data (i.e. ground truth). These data were supplemented with data from additional in-stream monitoring sites provided by the WA DOE. The in-stream data loggers were ideally located at regular intervals (*typically 10 river miles or less*) over the survey route. Meteorological data including air temperature and relative humidity were recorded using a portable weather station (*Onset*) located in Cashmere, WA near the confluence of Mission Creek and the Wenatchee River. Figure 1 illustrates the location of the in-stream data loggers used to ground truth the TIR images.

Data Processing

Measured radiance values contained in the raw TIR images were converted to temperatures based on the emissivity of water, atmospheric transmission effects, ambient background reflections, and the calibration characteristics of the sensor. The atmospheric transmission value was modeled based on the air temperatures and relative humidity recorded at the time of the survey. The radiant temperatures were then compared to the kinetic temperatures measured by the in-stream data loggers. The in-stream data were assessed at the time the image was acquired, with radiant values representing the median of ten points sampled from the image at the data logger location. Calibration parameters were fine-tuned to provide the most accurate fit between the radiant and kinetic temperatures.

Once the TIR images were calibrated, they were integrated into a GIS in which an analyst interpreted and sampled stream temperatures. Sampling consisted of querying radiant temperatures (pixel values) from the center of the stream channel and saving the median value of a ten-point sample to a GIS database file (Figure 2). The temperatures of detectable surface inflows (i.e. surface springs, tributaries) were also sampled at their mouth. In addition, data processing focused on interpreting spatial variations in surface temperatures observed in the images. The images were assigned a river mile based on a 1:100k routed GIS stream coverage from the Environmental Protection Agency (*Note: measures assigned from this coverage may not match stream measures derived from other map sources*).

The median temperatures for every sampled image of each surveyed stream were plotted versus the corresponding river mile to develop a longitudinal temperature profile. The profile illustrates how stream temperatures vary spatially along the stream gradient. The location and median temperature of all sampled surface water inflows (e.g. tributaries, surface springs, etc.) are included on the plot to illustrate how these inflows influence the main stem temperature patterns. Where applicable, tributaries or other features that were detected in the imagery, but were not sampled due to their small size (*relative to pixel size*) or the inability to see the stream through riparian vegetation are included on the profile to facilitate the interpretation of the spatial patterns.

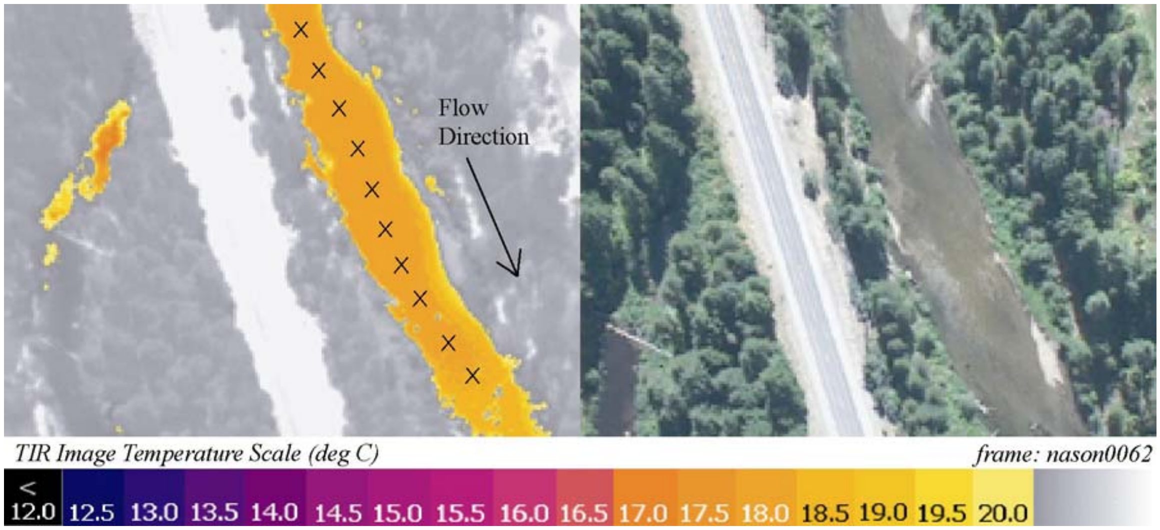

Figure 2 – TIR/color video image pair showing how temperatures are sampled from the TIR images. The black *X's* on the TIR image show typical sampling locations near the center of the stream channel. The recorded temperature for this image is the median of the sample points.

TIR Image Characteristics

Thermal infrared sensors measure TIR energy emitted at the water's surface. Since water is essentially opaque to TIR wavelengths, the sensor is only measuring water surface temperature. Thermal infrared data accurately represents bulk water temperatures where the water column is thoroughly mixed. However, thermal stratification can form in reaches that have little or no mixing. Thermal stratification in a free flowing river is inherently unstable due to variations in channel shape, bed composition, and in-stream objects (i.e. rocks, trees, debris, etc.) that cause turbulent flow. In the TIR images, indicators of thermal stratification include cool water mixing behind in-stream objects and/or abrupt transitions in stream temperatures. Occurrences of thermal stratification interpreted during analysis are identified in the results section for each survey.

Thermal infrared radiation received at the sensor is a combination of energy emitted from the water's surface, reflected from the water's surface, and absorbed and re-radiated by the intervening atmosphere. Water is a good emitter of TIR radiation and has relatively low reflectivity (approximately 4 to 6% of the energy received at the sensor is due to ambient reflections). During image calibration, a correction is included to account for average background reflections. However, variable water surface conditions (i.e. riffle versus pool), slight changes in viewing aspect, and variable background temperatures (i.e. sky versus trees) can result in differences in the calculated radiant temperatures within the same image or between consecutive images. The apparent temperature variability is generally less than 0.6^{o}C (Torgersen et al. 2001). However, the occurrence of reflections as an artifact (or noise) in the TIR images is a consideration during image interpretation and analysis. In general, apparent stream temperature changes of < 0.6^{o}C are not considered significant unless associated with a point source.

In stream segments with flat surface conditions (i.e. pools), relatively low mixing rates, or observed variations in spatial temperature patterns can be the result of differences in the instantaneous heating rate at the water's surface. In the TIR images, indicators of differential surface heating include seemingly cooler radiant temperatures in shaded areas compared to surfaces exposed to direct sunlight. Shape and magnitude distinguish spatial temperature patterns caused by tributary or spring inflows from those resulting from differential surface heating. Unlike with thermal stratification, surface temperatures may still represent bulk water conditions if the stream is mixed. Temperature sampling along the center of the stream channel (Figure 2) minimizes variability due to differences in surface heating rates. None-the-less, differences in surface heating combined with ambient reflection can confound interpretation of thermal features, especially near the riverbank.

A small stream width logically translates to fewer pixels "in" the stream and greater integration with non-water features such as rocks and vegetation. Consequently, a narrow channel (relative to the pixel size) can result in higher inaccuracies in the measured radiant temperatures (Torgersen et. al. 2001). In some cases, small tributaries were detected in the images, but not sampled due to the inability to obtain a reliable temperature sample. [2]

Results

Weather Conditions

Weather conditions for the times of the surveys are summarized in Table 2. Overall conditions were considered good for the TIR surveys with warm air temperatures and mostly clear skies.

Table 2 – Meteorological conditions recorded at the town of Cashmere, WA on the afternoon of August 11-12, 2003.

Time	Air Temp (*F)	Air Temp (*C)	RH (%)	Air Temp (*F)	Air Temp (*C)	RH (%)
	8/11/03			*8/12/03*		
13:00	82.2	27.9	28.1	80.1	26.7	24.9
13:30	83.0	28.3	26.3	81.5	27.5	21.3
14:00	83.7	28.7	25.4	83.0	28.3	20.5
14:30	83.7	28.7	23.5	81.5	27.5	23.5
15:00	85.1	29.5	22.2	81.5	27.5	23.1
15:30	80.8	27.1	30.0	81.5	27.5	30.0
16:00	81.5	27.5	26.3	81.5	27.5	24.0
16:30	83.7	28.7	24.4	80.1	26.7	26.3
17:00	82.2	27.9	25.8	81.5	27.5	27.2

[2] Features that are detected in the imagery, but not sampled for temperature are noted in the comment attribute of the flight point coverage.

Thermal Accuracy

Table 3 summarizes a comparison between the kinetic[3] temperatures recorded by the in-stream data loggers and the radiant temperatures derived from the TIR images. Overall, the range of differences between the radiant temperatures and kinetic temperatures were well within the desired accuracy of ±0.5°C. Accuracies were also typical of those observed for TIR surveys in the Pacific Northwest over the past 5 years.

Table 3 – Comparison of ground-truth water temperatures (Kinetic) with the radiant temperatures for streams surveyed in the Wenatchee River Basin, WA.

Image	Time	RM	Kinetic °C	Radiant °C	Difference °C
Peshastin Creek (avg. diff. = 0.4°C)					
pesh0029	14:14	0.4	21.6	21.3	0.3
pesh0377	14:26	8.1	15.9	16.4	-0.5
pesh0401	14:27	8.8	15.2	15.5	-0.3
pesh0412	14:27	9.1	17.5	17.7	-0.2
pesh0548	14:32	11.1	20.0	19.7	0.3
pesh0714	14:37	14.2	18.4	17.8	0.6
Mission Creek (avg. diff. = 0.4°C)					
miss0001	13:27	n/a	21.4	20.5	0.9
miss0068	13:29	1.1	18.7	19.2	-0.5
miss0248	13:35	4.4	18.3	18.2	0.1
miss0258	13:44	4.5	17.9	18.5	-0.6
miss0454	13:42	7.3	16.4	16.4	0.0
miss0459	13:43	7.3	16.4	16.2	0.2
miss0500	13:44	8.1	17.1	16.7	0.4
Chumstick Creek (avg. diff = 0.1°C)					
chum0044	14:58	0.3	14.8	14.7	0.1
chum0753	15:21	8.8	16.5	16.5	0.0
Nason Creek (avg. diff = 0.2°C)					
nason0043	13:54	0.6	17.9	17.8	0.1
nason0416	14:06	7.3	17.3	17.1	0.2
nason1064	14:28	17.8	15.0	15.2	-0.2
nason1455	14:41	24.5	12.4	12.6	-0.2

The Mission Creek flight showed the widest range of differences (-0.6°C to 0.9°C) between the kinetic and radiant temperatures. Although it is not possible to definitively verify the source, we believe that the differences may have been due (at least in part) to small channel widths combined with masking of the stream surface by riparian vegetation in the lower five miles. The possibility of hybrid pixels increases under these conditions resulting in potentially higher radiant temperatures (*references TIR Image Characteristics*). This pattern is reflected in the accuracy table with radiant temperatures

[3] Optical Stowaways used to ground truth the imagery have an advertised accuracy of ±0.2°C. The accuracy of each unit was verified prior to the field season and audited using a digital thermometer at each site.

slightly warmer than kinetic temperatures in the lower five miles and slightly cooler in areas where the water's surface was more clearly visible (*note: sensor in image miss0001 was located in the Wenatchee River*).

Temporal Differences

Figure 3 shows continuous in-stream temperature measurements in relation to the time of the TIR survey for a single location in each stream with the exception of Brender Creek (which had no in-stream sensors). Although not comprehensive, the intent of these plots is to provide some measure of the timing of the TIR flight in relation to the diurnal temperature cycle and assess the magnitude of temperature change that may have occurred during the time span of the survey.

As shown, the TIR surveys were conducted just prior to the recorded daily maximum temperatures on Mission, Chumstick, and Nason Creeks and during the daily stream temperature maximum on Peshastin Creek. Due to the relatively short durations of the individual surveys, in-stream temperatures did not change more than 0.4°C during the time span of the survey at any of these locations.

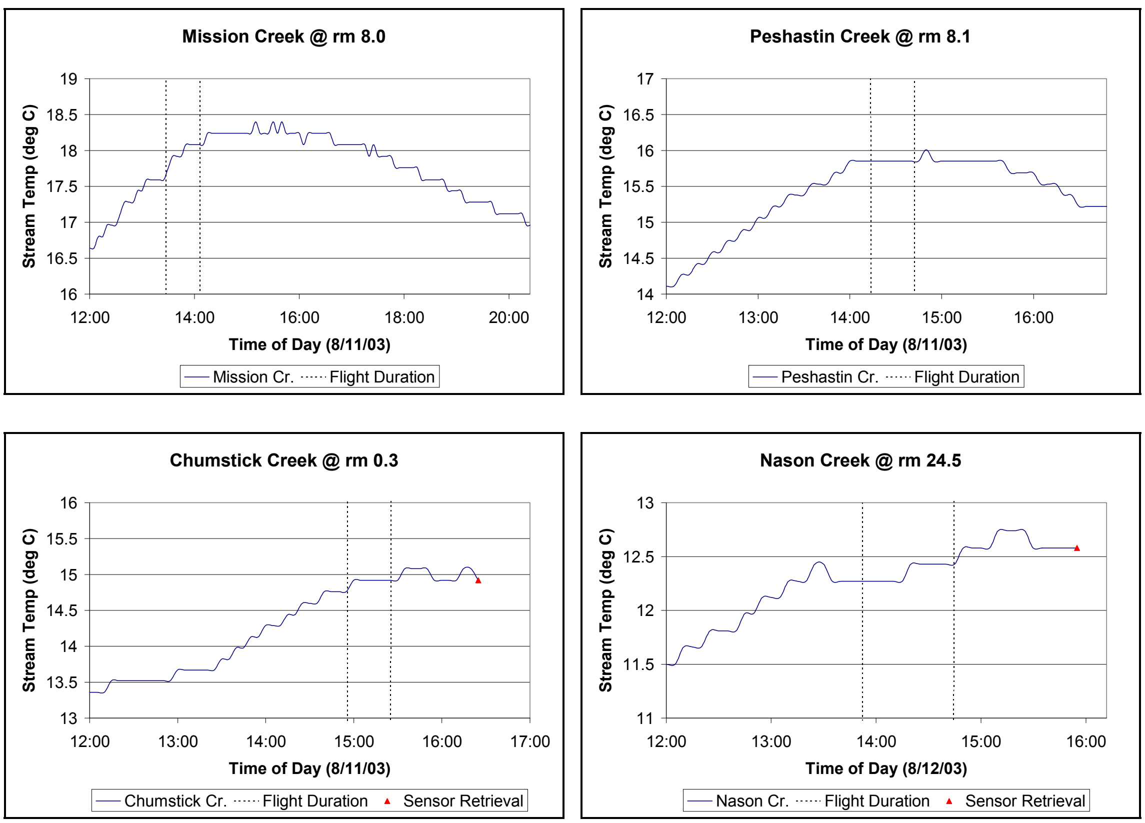

Figure 3 – Diurnal stream temperature variation during the afternoons of the TIR surveys measured at one monitoring site each on Nason, Peshastin, Mission and Chumstick Creeks. The plots show the variations in relation to the time of the flight.

Longitudinal Temperature Profiles

Mission Creek

Median radiant temperatures were plotted versus river mile for Mission Creek (Figure 4). One characteristic of the Mission Creek survey was that the stream surface was intermittently masked by vegetation and appeared dry between river miles 2.3 and 2.6. Since radiant temperatures could only be sampled when surface water was clearly visible, sampling was discontinuous in the lower five river miles including through the town of Cashmere, WA. The longitudinal profile (Figure 4) shows sample points that were not continuous connected by a broken line. In this case, sample points were considered continuous if they were taken at intervals less than ¼ miles. Over the full survey, the small stream size and masking from vegetation made it difficult to identify tributaries and other surface inflows.

The TIR survey concluded at the confluence of the East Fork Mission Creek where radiant stream temperatures measured ≈15.4^{o}C in both forks. Moving downstream, temperatures showed a general warming trend reaching a local maximum of 17.8^{o}C at river mile 8.4 before cooling again to ≈15.4^{o}C at river mile 7.0. Inspection of the topographic maps shows that Sand Creek joins Mission Creek within this reach. However, no surface inflows were detected during the analysis and the factors contributing to the cool reach were not directly apparent from the imagery.

From river mile 7.0 to the Wenatchee River confluence, water temperatures in Mission Creek exhibit a general warming trend. However, as mentioned previously, radiant temperature sampling was intermittent downstream of river mile 5 due to the lack of visible surface water in the imagery (Figure 5). Consequently, it was difficult to identify and assess sources of spatial temperature variability in this reach.

Brender Creek

Brender Creek was surveyed from the mouth for approximately 4.3 miles. A wetland area near river mile 0.3 appears to be the source of surface water that is detectable near the mouth. However, almost no continuous surface water was detectable upstream of the wetland area. Consequently, only a handful of radiant temperatures samples were taken of Brender Creek and these do not provide a meaningful representation of spatial temperature patterns in this creek.

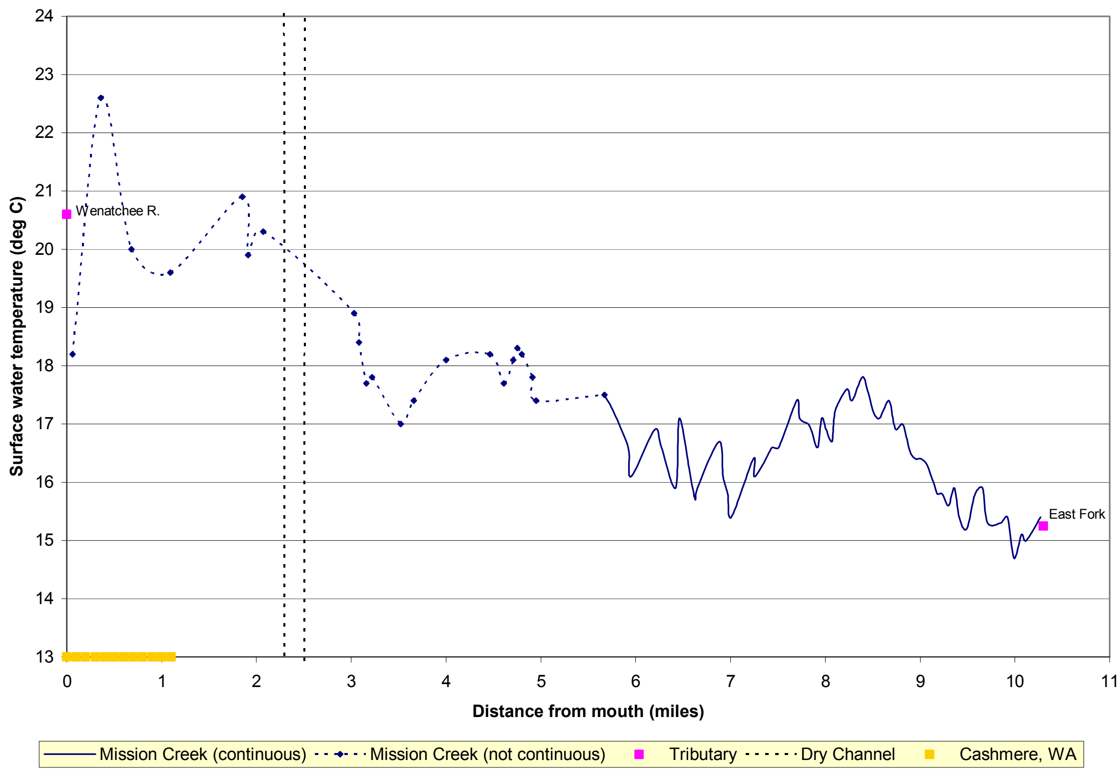

Figure 4 – Median channel temperature versus river mile for Mission Creek (8/11/03).

Figure 5 - TIR/color video image showing conditions characteristic of Mission Creek through the town of Cashmere, WA. The confluence of Brender Creek is visible at the very bottom of the image just upstream of the road. In this image, the water surface was visible only near the bridge. In other images, no discernable surface water was visible through the near stream vegetation.

Peshastin Creek

Median channel temperatures were plotted versus river mile for Peshastin Creek, WA (Figure 6). Tributaries and other surface inflows sampled during the analysis are labeled on the profile by river mile and summarized in Table 4. A number of mapped tributaries were detected in the imagery, but were not sampled due to their small size. These inflows often contribute to the spatial variability observed in the temperature profile. As a result, these locations were included on the profile to provide additional context for interpreting spatial temperature patterns. A flow diversion at river mile 2.4 was also included on the profile.

Middle Shaser Creek at river mile 15.3 was observed as a cooling source to Peshastin Creek and appeared to contribute significantly to Peshastin flows. Although the survey continued for another 1.2 miles upstream of Middle Shaser Creek, Peshastin Creek was very small (relative to pixel size) and difficult to discern through the vegetation.

Between river miles 15.3 and the Negro Creek confluence (river mile 11.0), radiant water temperatures in Peshastin Creek exhibited a high degree of local variability with sampled temperatures ranging between 16.6^{o}C and 20.5^{o}C. Due to the small stream size in the reach, one should expect greater apparent variability due to a higher frequency of hybrid pixels (*reference TIR image characteristics*), which would inherently increase the number of warmer samples. However, the TIR data also illustrates that much of the observed local spatial variability is due to the influence of cool water inflows. An apparent spring inflow at river mile 14.4 decreased stream temperatures locally by ≈1.6^{o}C. The inflow of King Creek similarly resulted in a localized decrease in stream temperature of ≈2.6^{o}C at river mile 13.9. Unsampled tributaries also contributed spatial temperature variability within this reach. For example, Culver Spring Creek was detected at river mile 12.9, but not visible enough in the imagery to obtain a representative temperature sample. None-the-less, a localized decrease in Peshastin Creek was observed at the confluence. A notable drop in sampled temperatures was observed at river mile 13.1, but was not associated with a surface water inflow. Review of the imagery shows that the apparent decrease occurs immediately downstream of one of the many locations where highway 97 crosses Peshastin Creek.

The inflow of Negro Creek (river mile 11.0) has a dramatic influence on water temperatures in Peshastin Creek (Figure 7). Stream temperatures increased over the next two miles, but the inflow of Ingalls Creek at river mile 9.1 effectively reset Peshastin Creek temperatures to ≈15.4^{o}C. Downstream of Ingalls Creek, stream temperatures showed considerably less localized variability than in the upstream reaches due presumably to the greater flow volumes contributed by the tributaries. However, the longitudinal profile shows distinct thermal patterns at a broader scale.

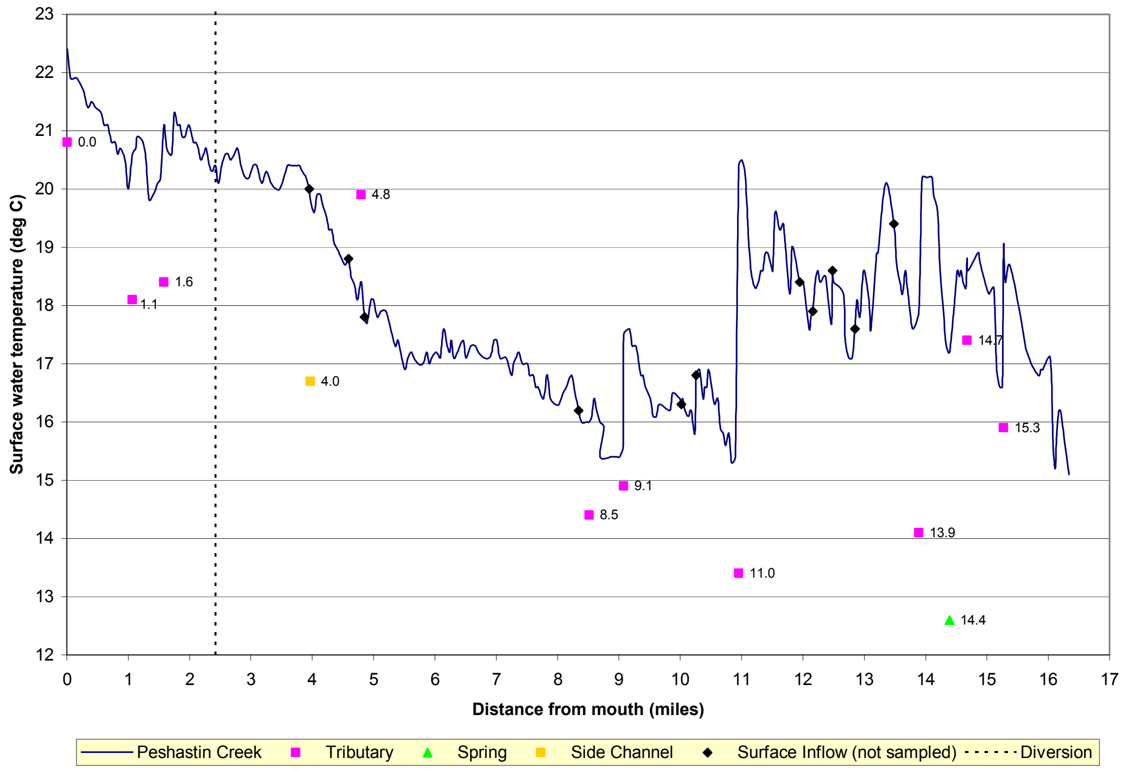

Figure 6 - Median channel temperatures versus river mile for Peshastin Creek (8/11/03). The plot also shows the locations of both surface inflows that were sampled during the analysis and those that were detected but not sampled.

Table 4 - Tributary and other surface inflows for Peshastin Creek.

Tributary Name	Image	km	mile	Tributary °C	Peshastin Cr. °C	Difference °C
Tributary						
Wenatchee R.	pesh0012	0.0	0.0	20.8	22.4	-1.6
Unnamed (RB)	pesh0059	1.7	1.1	18.1	20.6	-2.5
Unnamed (LB)	pesh0081	2.5	1.6	18.4	21.1	-2.7
Mill Cr (LB)	pesh0233	7.6	4.8	19.9	18.4	1.5
Hansel Cr (LB)	pesh0386	13.5	8.5	14.4	16.0	-1.6
Ingalls Cr (LB)	pesh0411	14.4	9.1	14.9	17.5	-2.6
Negro Cr (LB)	pesh0540	17.3	11.0	13.4	20.4	-7.0
King Cr (LB)	pesh0682	22.0	13.9	14.1	17.9	-3.8
Transen Cr (RB)	pesh0727	23.3	14.7	17.4	18.8	-1.4
Middle Shaser Cr (LB)	pesh0760	24.2	15.3	15.9	19.0	-3.1
Spring						
Spring (LB)	pesh0709	22.8	14.4	12.6	17.2	-4.6
Side Channel						
Side Channel (RB)	pesh0194	6.3	4.0	16.7	19.8	-3.1

LB = left bank, RB = right bank looking downstream.

Downstream of Ingalls Creek, stream temperatures increased to ≈17.2°C at river mile 7.4 and remained relatively consistent to river mile 5.5 (17.2°C, ±0.4°C). From river mile 5.5 to river mile 3.8, Peshastin Creek exhibited steady and continuous longitudinal heating with water temperatures reaching 20.4°C at river mile 3.8. Inspection of the topographic base maps shows that longitudinal heating generally occurs as the stream transitions from the Wenatchee National Forest to the Wenatchee River Valley. The increased heating rate through this segment suggests a thermal response due (at least in part) to changing channel and terrain morphology.

Stream temperatures continued to increase between river mile 3.8 and the mouth, but at a slower rate than observed in the upstream reach. A slight increase in longitudinal heating was observed downstream of the dam. Two surface water inflows downstream of the diversion resulted in some localized cooling.

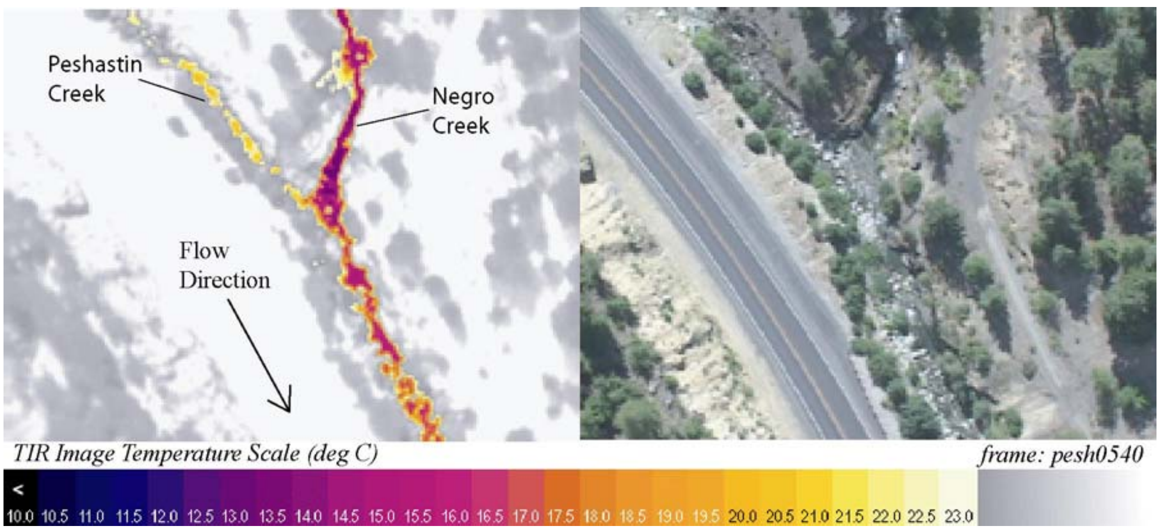

Figure 7 - TIR/color video image showing the inflow of Negro Creek (13.4°C) to Peshastin Creek (20.4°C) at river mile 11.0.

Chumstick Creek

Chumstick Creek presented a unique challenge for airborne stream temperature mapping. At its mouth, Chumstick Creek contributed relatively cool water (14.2^{o}C) to the Wenatchee River and was easily identified in the imagery (Figure 8). Although the stream channel was partially masked by vegetation through the lower 1.8 river miles *(just downstream of confluence of Eagle Creek*), surface water was detected intermittently in the imagery and radiant temperature samples were taken wherever surface water was identified. However, detection of surface water became less frequent as the survey progressed upstream. In some locations, surface water was visible, but the ability to accurately sample temperatures was greatly diminished by the combination of small channel size and stream side vegetation. In other locations, surface water could simply not be detected in the imagery (Figure 9).

When surface water was visible, sampled temperatures were generally much cooler than the surrounding vegetation. Past TIR surveys in the Pacific Northwest have shown that when contrast exists between the water temperature and the apparent temperature of vegetation, the stream is at least detectable even through dense canopies - although maybe not visible enough to sample. Detection of surface water on Chumstick Creek was not limited to vegetated areas. Surface water was also not visible in some stream segments where vegetation did not preclude detection. These segments, combined with previous experience in detecting streams through vegetation, suggest that surface water was intermittent along the length of Chumstick Creek and the inability to detect the stream in vegetated areas may have been simply due to a lack of surface water. Table 5 provides a general summary of sampling conditions along Chumstick Creek.

Figure 8 - TIR/color video image pair showing the confluence of Chumstick Creek (14.5^{o}C) and the Wenatchee River (19.7^{o}C).

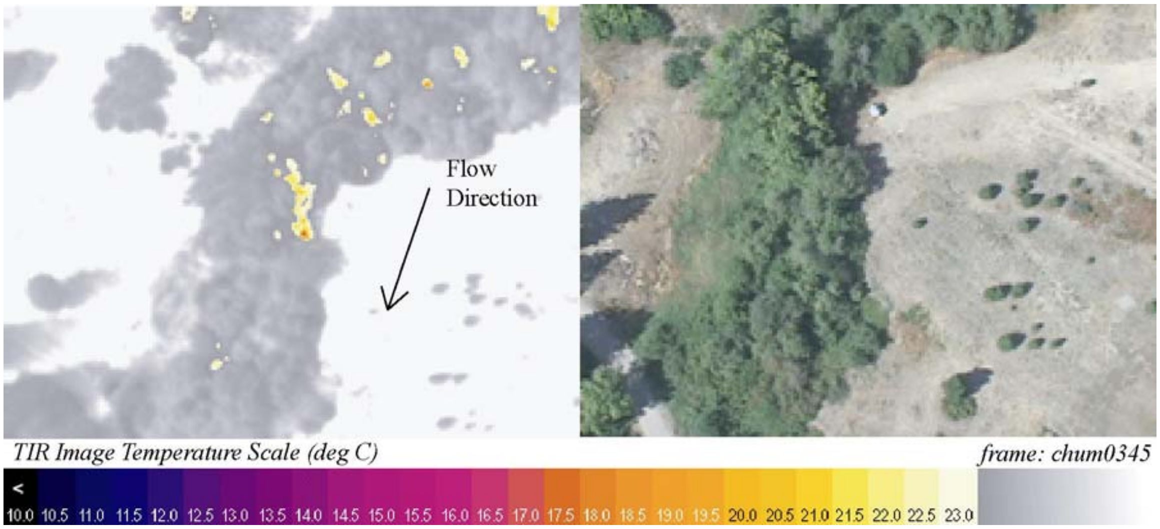

Figure 9 - TIR/color video image pair showing Chumstick Creek at river mile 3.4. The images provide an example of channel and riparian conditions characteristic of the Chumstick Creek survey.

Table 5 - General summary of conditions observed during the analysis of Chumstick Creek imagery.

Images Frames	Miles	Characteristic	Sampling
chum0028 - 0186	0.0 – 1.5	Surface water detected continuously, but some vegetation masking.	10 sample/1.5 miles
chum0187 - 0272	1.5 – 2.6	Vegetation masking. No surface water detected in less vegetated areas.	Not sampled
chum0272 - 0509	2.6 - 5.7	Vegetation with occasionally visible surface water. Uncertain whether surface water is continuous or intermittent.	9 sample/3.1 miles
chum0510 - 0717	5.7 – 8.3	Surface water is clearly intermittent	1 sample/2.6 miles
Chum0717 - 0753	8.3 – 8.8	Surface water visible, but very small channel.	5 sample/0.5 miles
Chum0753 - 0856	8.8 – 10.6	Vegetation masking. Uncertain whether surface water is continuous or intermittent.	1 sample/1.8 miles

Although the sampling of Chumstick Creek was intermittent, a plot of median radiant temperatures versus river miles still provides insight into the thermal structure of Chumstick Creek (Figure 10). Sample points were shown on the plot and connected with a dashed line in order to illustrate coarse trends in water temperatures. Since sampling was not continuous, this profile does not show spatial temperature patterns between sample points.

The profile does show that all sampled temperatures were below ≈17.1°C. On a stream this small, one might expect some measurable level of longitudinal heating between sample points. This trend of cool water points reinforces a hypothesis that much of the flow in Chumwater Creek is sub-surface with only intermittent surface water.

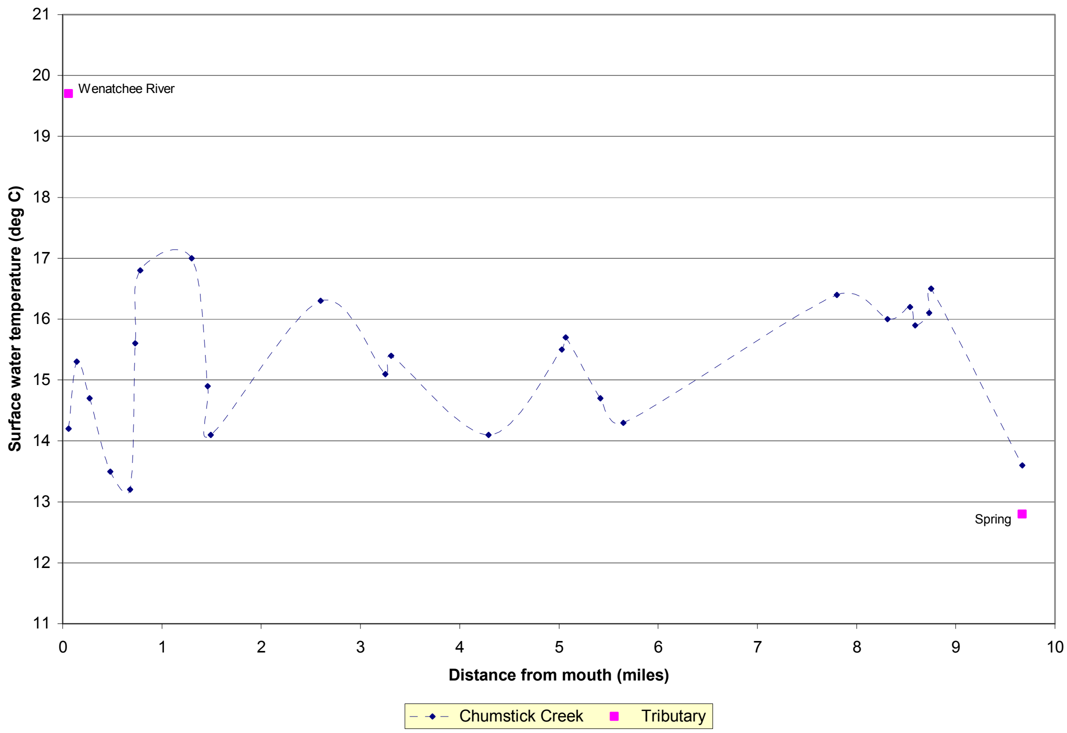

Figure 10 - Median channel temperatures for sampled points along Chumstick Creek.

Nason Creek

Median radiant temperatures were plotted versus river mile for Nason Creek (Figure 11). Tributaries and other sampled inflows (i.e. springs, side channels) are labeled by river mile on the profile with their name and temperature summarized in Table 6. The profile also shows the location of tributaries that were detected during the image analysis, but were not visible enough to obtain an accurate radiant temperature sample. These locations were included to provide additional context for assessing observed spatial temperature patterns.

Overall, Nason Creek exhibited a general pattern of downstream warming with thermal variability occurring at multiple scales along the profile. At the upstream end of the survey, water temperatures were cool (<11.0°C @ river mile 25.0) and increased rapidly reaching ≈13.9°C at river mile 23.2. A sharp decrease (-1.7°C) was observed at river mile 22.9. Although the source of cooling at this location was not directly apparent from the imagery, a spring sampled at river mile 22.7 and Smith Brook Creek (not sampled) mapped at river mile 22.7 may have contributed to this decrease. Moving downstream, water temperatures increased rapidly reaching 14.6°C at river mile 22.0 before remaining relatively consistent with only local thermal variability (±0.7°C) to river mile 20.6. At river mile 20.6, the inflow of Mill Creek (13.3°C) dramatically lowers the water temperatures in Nason Creek (Figure 12).

Downstream of Mill Creek, water temperatures in Nason Creek exhibited fewer dramatic fluctuations and more distinct reach scale patterns of warming and cooling. Local warming trends were observed between river miles 18.8 and 17.6 and between river miles 15.0 and 13.6. The reach with the most sustained longitudinal heating occurred between river miles 10.6 and 3.5 where stream temperatures, at the time of the survey, increased from 15.3°C to 19.1°C. Local cooling was observed in two reaches. Stream temperatures decreased from 15.7°C to 13.9°C between river miles 16.5 and 15.0. The inflow of Whitepine Creek at river mile 15.3 contributed in part to the observed temperature minimum. However, the cooling trend started upstream of the Whitepine Creek suggesting that other factors contributed to the overall trend. Another area of localized cooling (-1.5°C) was observed between river mile 3.2 and 2.6. The factors contributing to this trend were not apparent from the imagery. Between river mile 20.6 and the mouth, three distinct reaches had relatively consistent temperatures throughout. Water temperatures in each of these reaches were much less than measured air temperatures and one may expect some level of longitudinal heating in the absence of some buffering process. Factors controlling stream temperatures through these reaches are an area for further analysis.

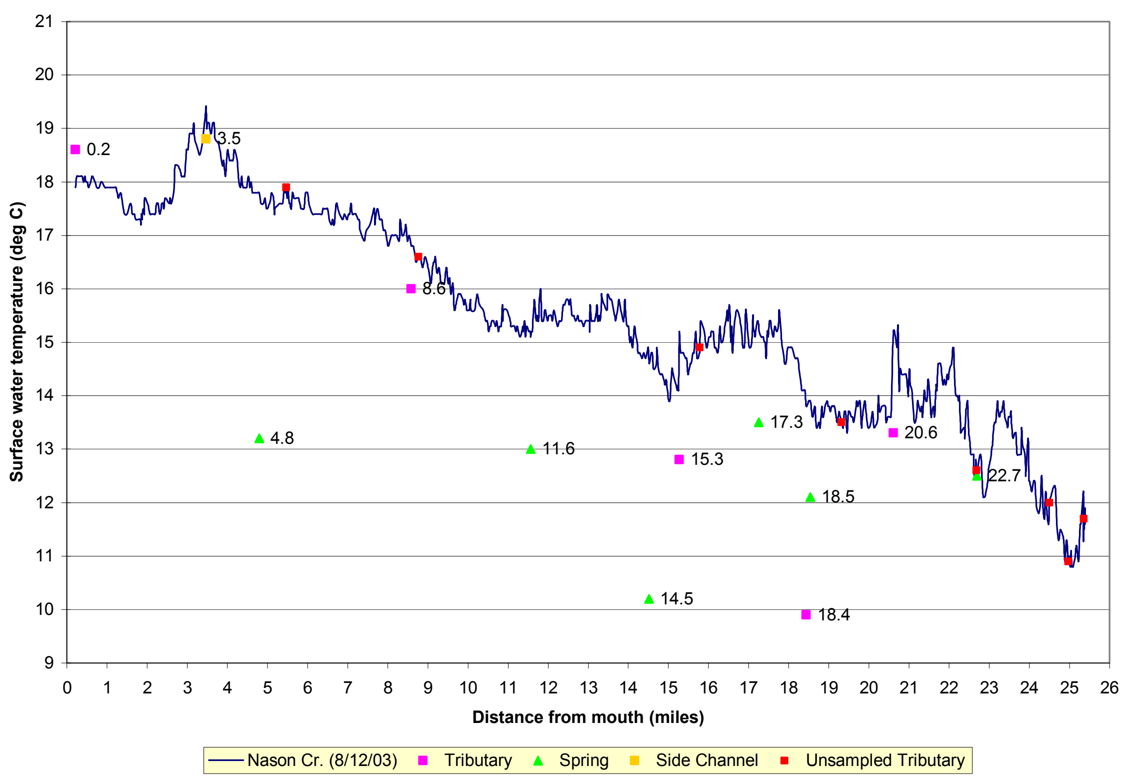

Figure11 - Median channel temperatures versus river mile for Nason Creek (8/12/03). Surface water inflows are labeled by river mile.

Table 6 - Tributary and other surface water inflows for Nason Creek.

Name	Image	Km	Mile	Tributary °C	Nason Cr. °C	Difference °C
Tributary						
Wenatchee R. (LB)	nason0018	0.3	0.2	18.6	17.9	0.7
Butcher Cr. (LB)	nason0470	13.8	8.6	16.0	16.8	-0.8
Whitepine Cr. (RB)	nason0891	24.6	15.3	12.8	15.2	-2.4
Unnamed Trib. (RB)	nason1092	29.7	18.4	9.9	13.8	-3.9
Mill Cr. (RB)	nason1212	33.2	20.6	13.3	15.2	-1.9
Spring						
Spring (RB)	nason0283	7.7	4.8	13.2	17.8	-4.6
Spring (RB)	nason0638	18.6	11.6	13.0	15.1	-2.1
Spring (RB)	nason0808	23.4	14.5	10.2	14.6	-4.4
Spring (LB)	nason1024	27.8	17.3	13.5	15.3	-1.8
Spring (RB)	nason1096	29.8	18.5	12.1	13.9	-1.8
Spring (LB)	nason1338	36.5	22.7	12.5	12.6	-0.1
Side Channel						
Side Channel (RB)	nason0210	5.6	3.5	18.8	19.4	-0.6

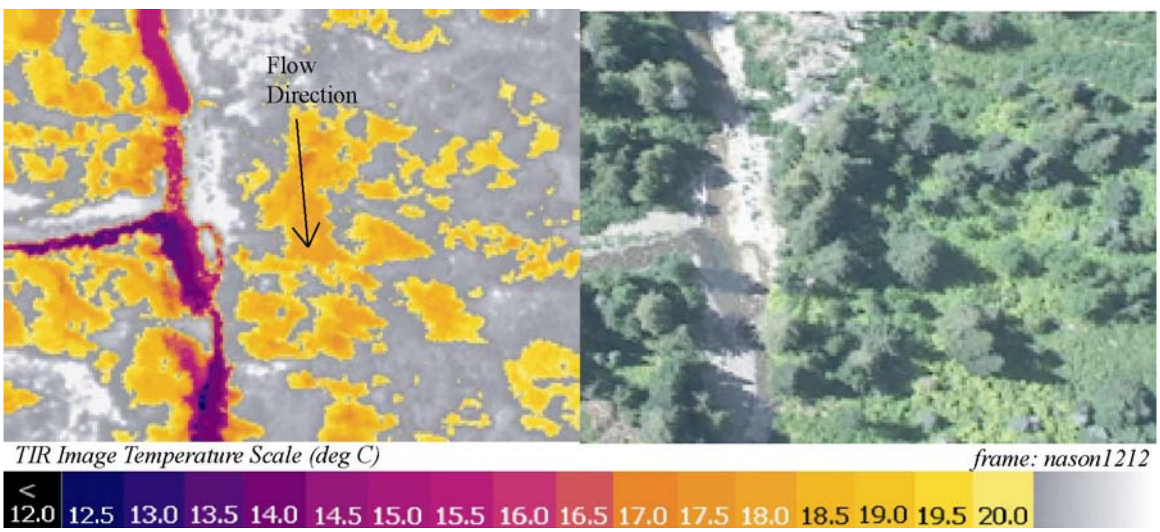

Figure 12 - TIR/color video image showing the confluence of Mill Creek and Nason Creek at river mile 20.6. The Mill Creek inflow lowered water temperatures in Nason Creek by ≈1.6°C.

Discussion

TIR remote sensing surveys were successfully conducted on selected streams in the Wenatchee River sub-basin. Nason and Peshastin Creeks have continuous surface flow throughout the survey extents. Longitudinal temperature profiles were developed for these streams which illustrate broad scale spatial temperature patterns. The analysis was further able to identify sources of thermal cooling and loading such as springs and tributaries that were visible in the imagery. A longitudinal temperature profile was similarly produced for Mission Creek. However, radiant temperature sampling was not continuous in the lower five miles due to almost complete masking of the stream surface by vegetation. Continuous surface flow could not be detected in Chumstick and Brender Creek due either to a lack of surface water itself or masking of the stream surface by riparian vegetation. A longitudinal temperature profile was developed for Chumstick Creek where surface water was visible. Although not continuous, the Chumstick Creek profile provides a synoptic view of stream temperatures at locations that could be reliably sampled.

Nason Creek was flown using similar methods and instrumentation on August 14, 2001 (WS, LLC 2002). The data from the two surveys presents a unique opportunity to compare spatially continuous temperature patterns from different years (Figure 13). Visual inspection of the two profiles shows that, although absolute temperatures were warmer during the 2001 survey, broad scale spatial temperature patterns were consistent. Reaches that exhibited longitudinal heating in 2001 were the same reaches that showed heating in 2003. However, the profiles also show that in the warmer year (2001), the rates were generally higher (i.e. ^{o}C/river mile) resulting in more dramatic local temperature maximums. Like-wise, locally cool areas were consistent between the two years. The consistencies between years further illustrate that the longitudinal profiles provide a good spatial template for understanding how the stream is thermally structured. This template can be used for directing future temperature analysis of the stream including the placement of in-stream sensors and other field based surveys. Follow-on study should further contrast the spatial temperatures patterns between the two years in order to better understand the stream's thermal response under different climatic conditions. Are cool areas consistent between years and are these temperatures stable with regard to the thermal requirements for salmonids? Have stream reaches changed with regard to channel and habitat conditions?

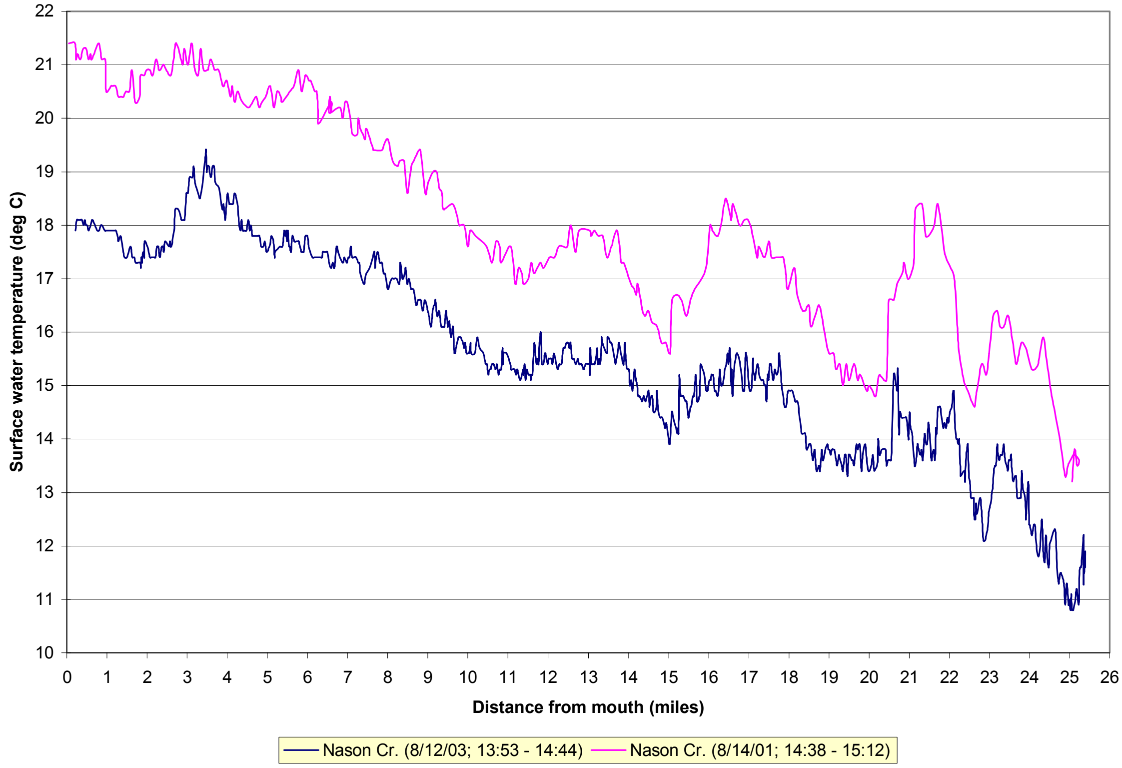

Figure 13 – Comparison of longitudinal temperature profiles derived from airborne TIR imagery collected on Nason Creek on August 12, 2003 and August 14, 2001.

Although conditions precluded radiant temperature sampling in portions of Mission and Chumstick Creeks and almost all of Brender Creek, the TIR images and associated true color imagery provide a valuable resource for assessing channel, habitat, and riparian conditions along these streams. These data can provide a more comprehensive understanding of fragmentation of surface water along the stream gradient. The images provided with the database may be further aggregated to form mosaics. These mosaics are great tools for illustrating specific conditions and can be used for planning fieldwork and in presentations.

This report provides an overview of the airborne TIR remote sensing surveys conducted in the Wenatchee River Sub-Basin on August 11-12, 2003. The report presents broad scale temperature patterns derived from the TIR imagery and offers observations on thermal features and conditions along each stream. The report is intended to document the surveys and provide a starting point for more in-depth analysis using the image database.

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Torgersen, C.E., R. Faux, B.A. McIntosh, N. Poage, and D.J. Norton. 2001. Airborne thermal remote sensing for water temperature assessment in rivers and streams. *Remote Sensing of Environment* 76(3): 386-398.

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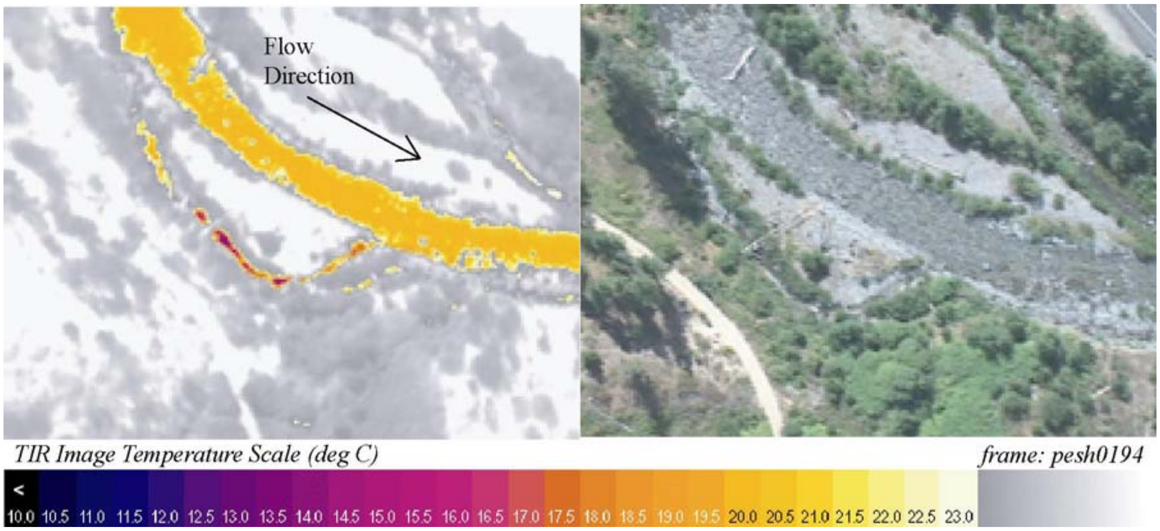
Appendix A - Selected Images

Mission Creek

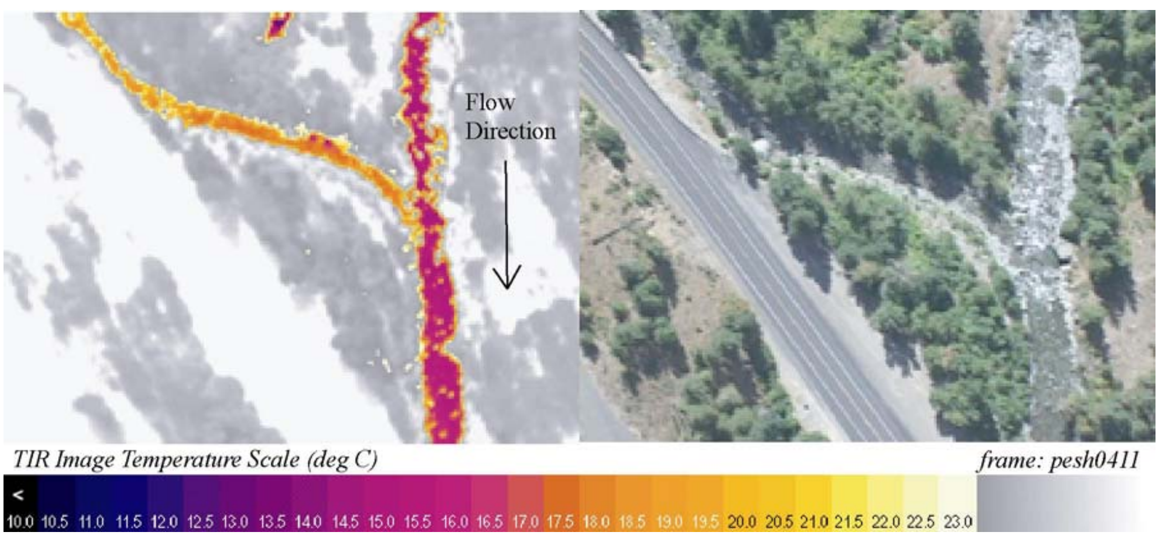
TIR/color video image pair showing an example of Mission Creek (river mile 2.4) and the difficulty in detecting surface water through this reach.

TIR/color video image pair showing an example of the conditions characteristic of the upstream reaches of the Mission Creek survey (river mile 8.6). In the upstream reaches, surface water was clearly visible and had significant thermal contrast from the surrounding vegetation. However, the vegetation precluded detecting small tributaries and other fine scale thermal inflows.

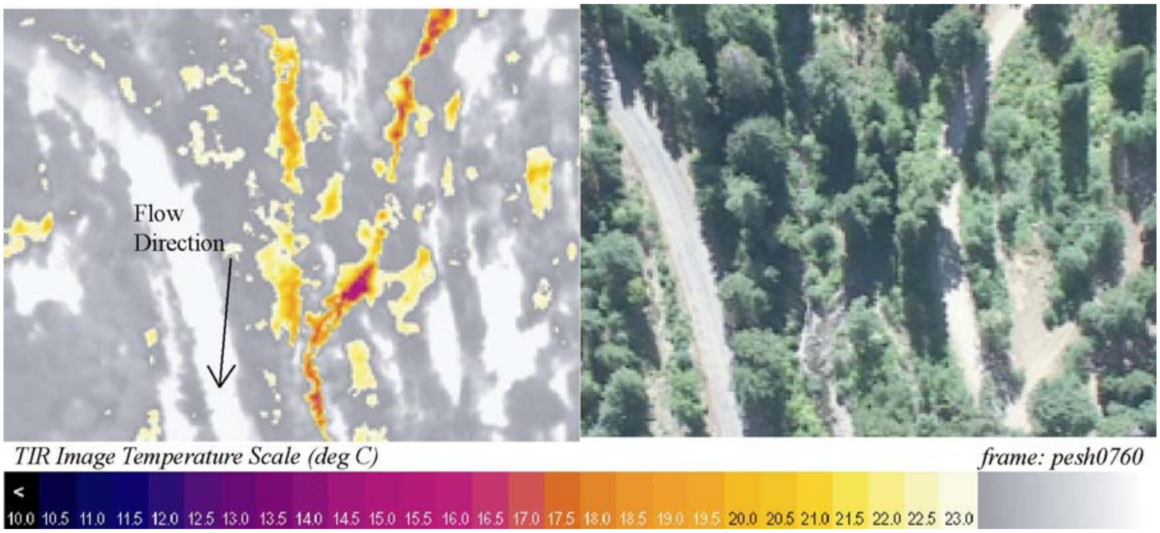
Peshastin Creek



TIR/color video image pair showing a cool side channel (16.7°C) on the right bank of Peshastin Creek (19.8°C) near the mapped confluence of Larsen Creek at river mile 4.0.

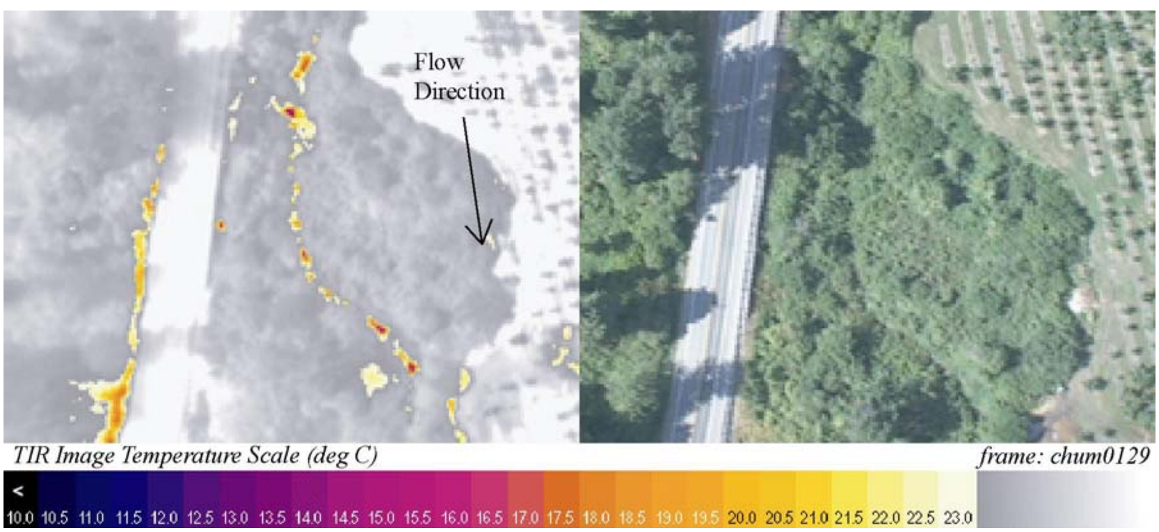


TIR/color video image pair showing the confluence of Ingalls Creek (14.9°C) to the left bank of Peshastin Creek (17.5°C) at river mile 9.1.

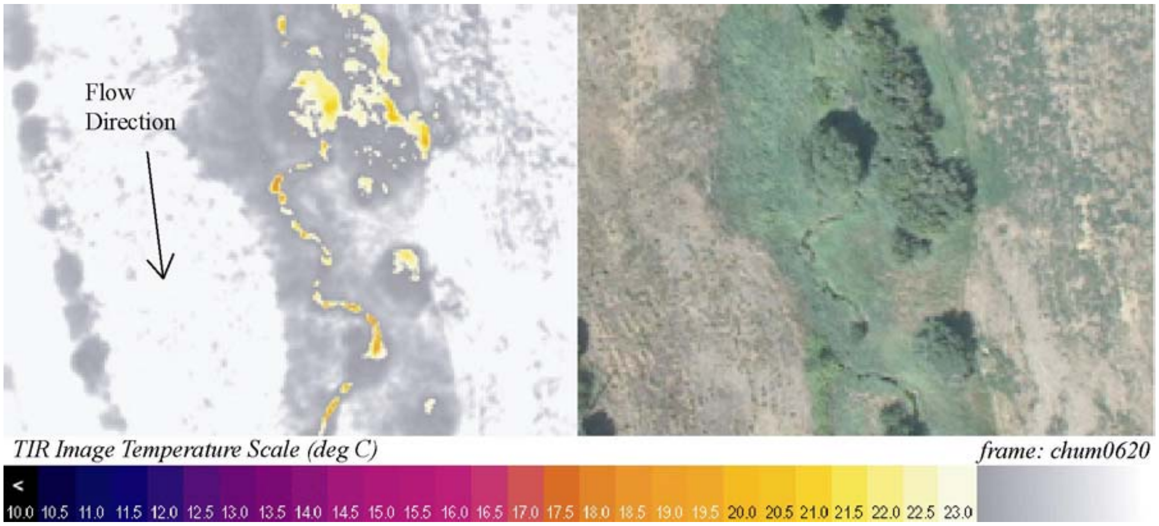


TIR/color video image pair showing the confluence of Middle Shaser Creek (15.9^{o}C) to the left bank of Peshastin Creek (19.0^{o}C) at river mile 15.3.

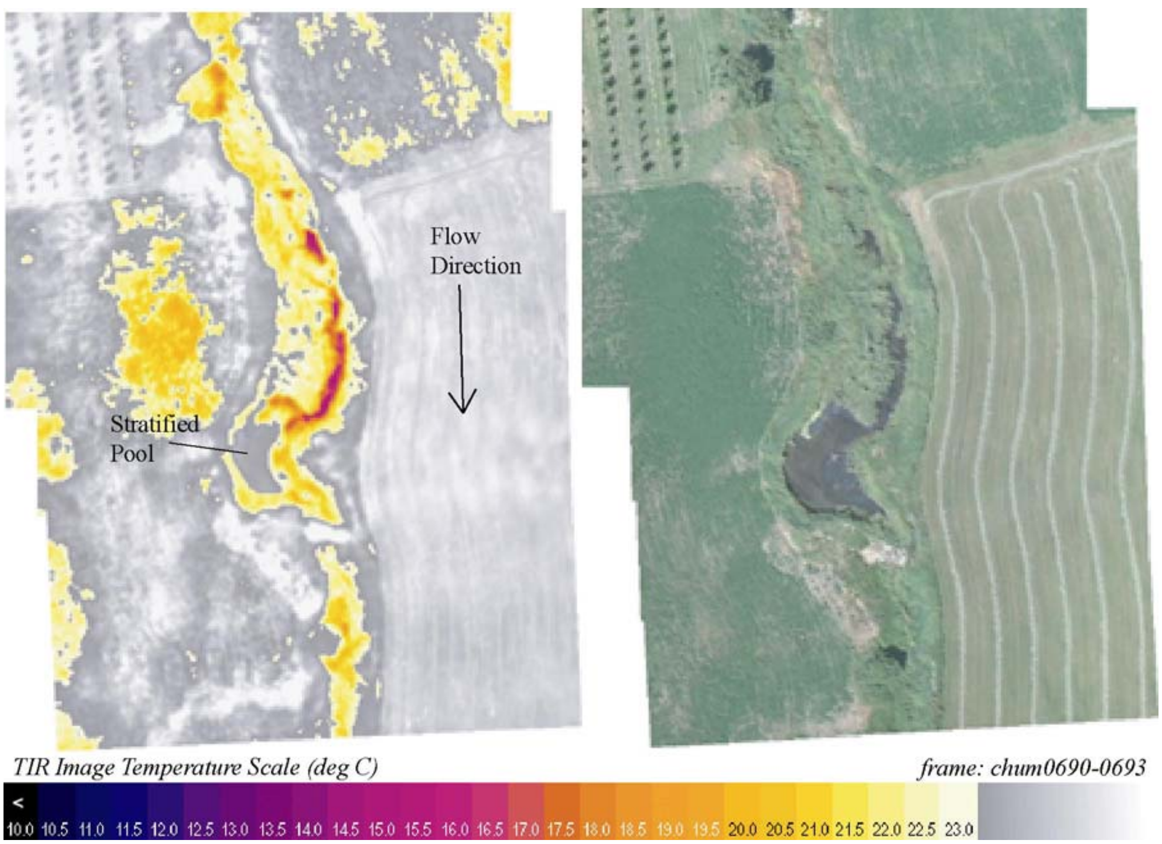
Chumstick Creek



TIR/color video image pair showing an area of Chumstick Creek at river mile 0.6 which is an example of the lack of visible surface water characteristic of Chumstick Creek.

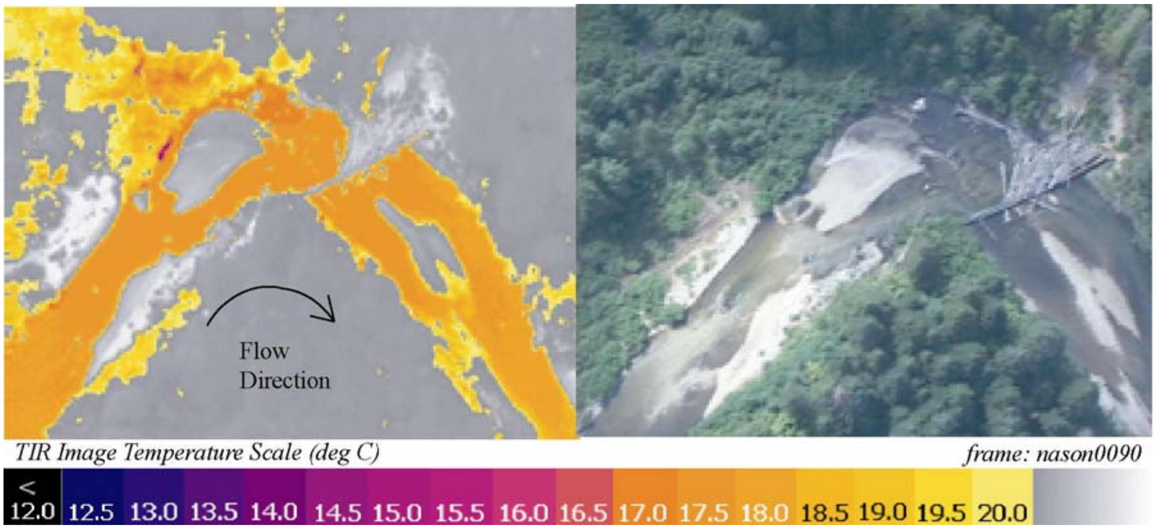


TIR/color video image pair showing Chumstick Creek at river mile 6.7 with very little visible surface water.

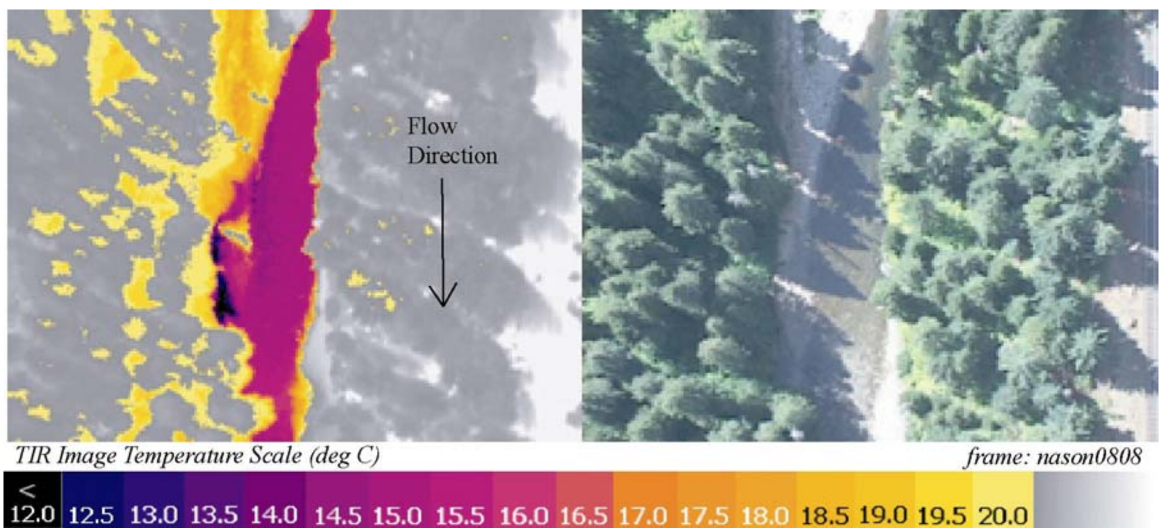


TIR/color video image pair showing a pool at river mile 7.8 of Chumstick Creek (16.4^{o}C), downstream of which there is no visible flow. Surface temperatures indicate that the pool is thermally stratified.

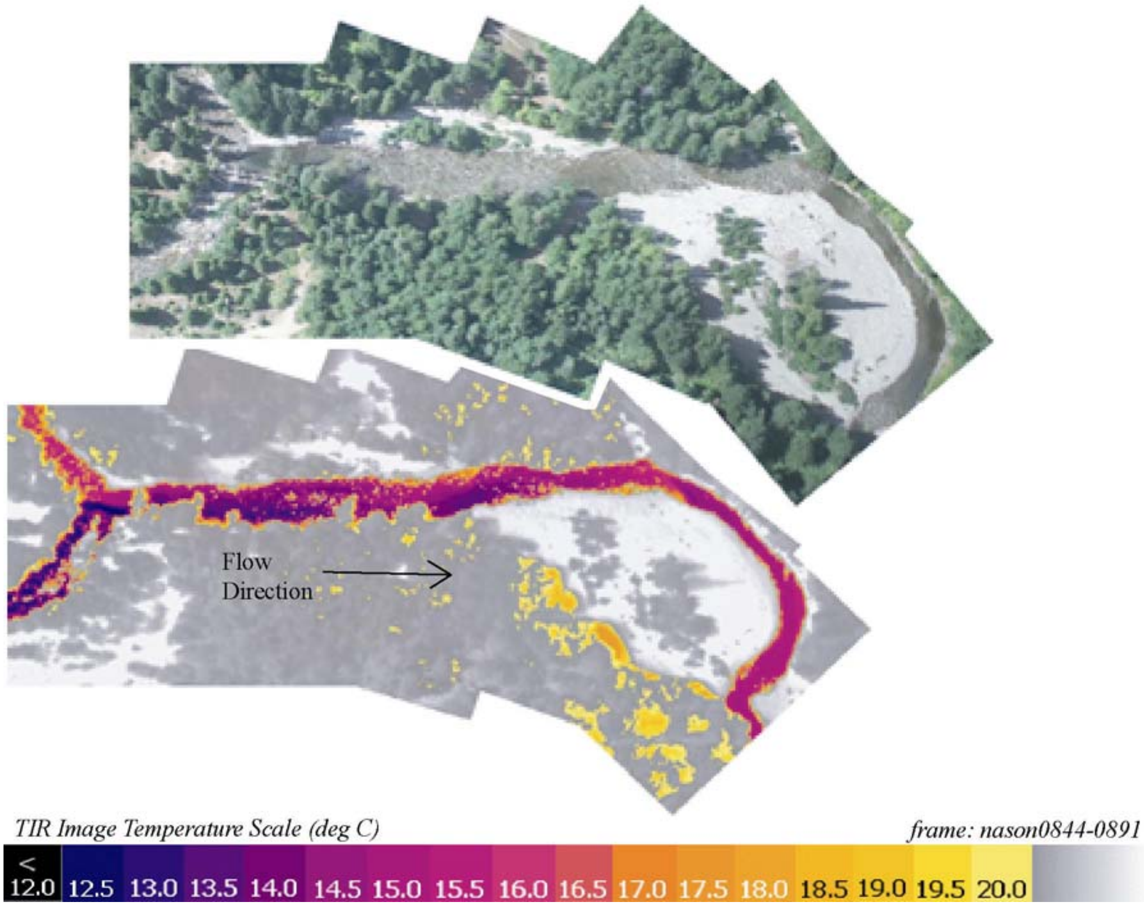
Nason Creek



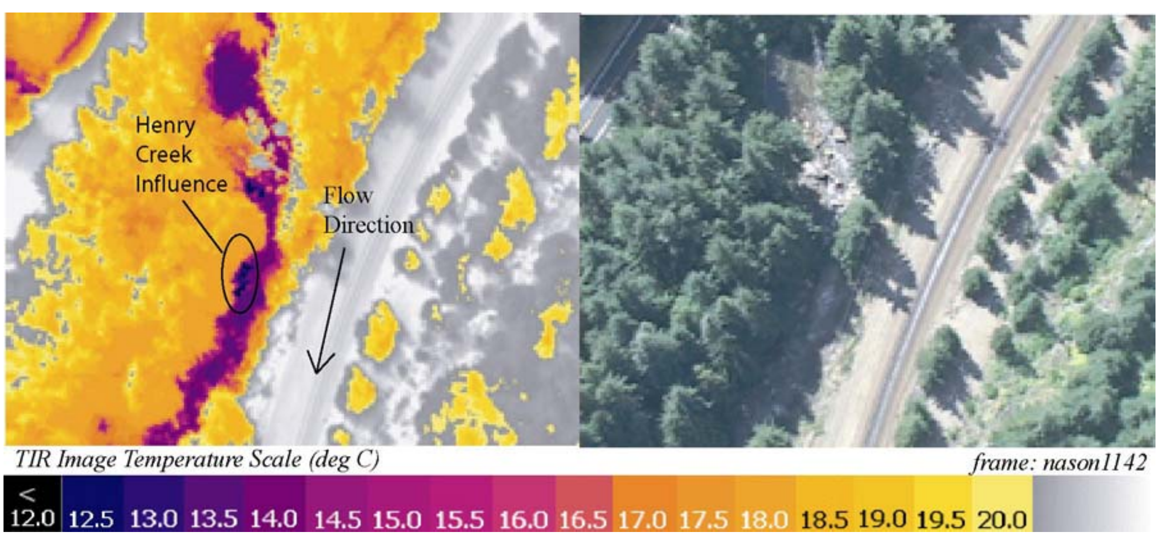
TIR/color video image pair showing an apparent spring (16.9°C) on the left bank of Nason Creek (17.4°C) at river mile 1.9.



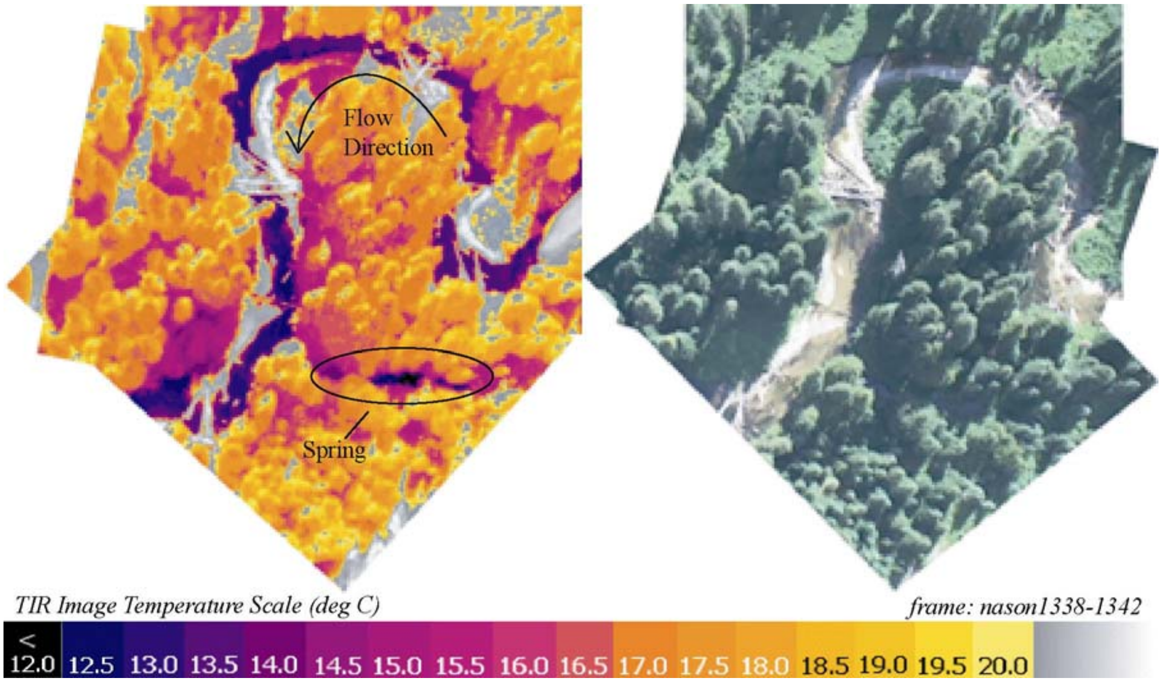
TIR/color video image pair showing an apparent spring on the right bank of Nason Creek (14.6°C) at river mile 14.5.



TIR/color video image pair showing the confluence of Whitepine Creek (12.8°C) to the right bank of Nason Creek (15.5°C) at river mile 15.2.



TIR/color video image pair showing the influence of Henry Creek (though it isn't visible through the vegetation) on the right bank of Nason Creek (13.5°C) at river mile 19.3.



TIR/color video image pair showing an apparent spring along the left bank of Nason Creek (12.6°C) at river mile 22.7.